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Abundant ϕ-meson production in $\bar{p}p$ annihilation at rest and strangeness in the nucleon

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Abstract

A large apparent violation of the OZI rule has recently been found in many channels in $\bar{p}p$ annihilation at LEAR. An interpretation of these data in terms of the "shake-out" and "rearrangement" of an intrinsic $\bar{\mathrm{s}}\mathrm{s}$ component of the nucleon wave function is proposed. This gives a channel-dependent, non-universal modification of the naïve OZI prediction. Within this approach, we interpret the strong excess of ϕ production in S-wave $\bar{\mathrm{p}}\mathrm{p}$ annihilations in terms of the polarization of the nucleon's $\bar{\mathrm{s}}\mathrm{s}$ component indicated by deep inelastic lepton-nucleon scattering experiments. This interpretation could be tested by measurements of the $f_2'(1525)/f_2(1270)$ production ratio in P-wave annihilations and by experiments with polarized beams and polarized targets. We also propose a test of the intrinsic strangeness hypothesis in ϕ production in high-momentum transfer processes, via a difference in constituent counting rules from gluon-mediated production.

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1 Introduction

According to the naïve constituent quark model, the proton wave function contains just two u-quarks and one d-quark. This model gives a good general picture of hadron structure at large distances, but probes of shorter distances and larger momentum transfers reveal more constituents, including a sea of q̄q (q=u,d,s) pairs and gluons. These evolve with momentum, in agreement with perturbative QCD, but there are indications that the nucleon wave function contains some s̄s pairs already at large distances or small momentum transfers, in the non-perturbative regime (for reviews, see [1]-[3]). This should not be unexpected, since non-perturbative QCD effects cause s̄s pairs to be present in the vacuum: $< 0\,|\bar{s}s|\,0 > \neq 0$, and soluble two-dimensional models [4] also predict the existence of non-perturbative s̄s pairs in the nucleon wave function. This possibility is also consistent with analytical [5] and lattice [6] determinations of the $\pi - N$ $\sigma-$ term.

Interesting experimental evidence for such an s̄s component comes from the apparent violation of the Okubo-Zweig-Iizuka (OZI) rule in the production of ϕ mesons in different reactions. According to the OZI rule [7], diagrams with disconnected quark lines should be negligible. Production of the ϕ meson is a particularly sensitive probe of the OZI rule because the ϕ is almost a pure s̄s state, containing just a small admixture of ūu+d̄d associated with a small deviation $\delta = \Theta - \Theta_i$ from the ideal mixing angle $\Theta_i = 35.3^0$. The OZI rule was used [8] to predict

$$R = \frac{\sigma(A + B \to \phi X)}{\sigma(A + B \to \omega X)} = \tan^2 \delta \cdot f \tag{1}$$

for any initial-state hadrons A,B and final-state hadrons not containing strange quarks, where f is a kinematical phase space factor. Using the theoretically-favoured quadratic Gell-Mann-Okubo mass formula, one finds $\Theta = 39^0$ and hence $R = 4.2 \cdot 10^{-3} f$. As we see in Table 1, many past experiments found an apparent excess of R above this OZI prediction, though this was not very dramatic: $R \leq (10 - 20) \cdot 10^{-3}$.

The significance of such an excess can be inferred from the parameter

$$Z = \frac{M(A + B \to \bar{s}s + X)}{[M(A + B \to \bar{u}u + X) + M(A + B \to \bar{d}d + X)]/\sqrt{2}} \tag{2}$$

which measures OZI-breaking in the amplitudes $M(A+B \to \bar{q}q+X)$, leading to the estimate

$$R = \left(\frac{Z + \tan\delta}{1 - Z\tan\delta}\right)^2 \cdot f \tag{3}$$

Values of $|Z|$ are also shown in Table 1, where we see that previous experiments indicate $|Z| \leq 0.1$. However, as we discuss later in this paper, much larger apparent violations of the OZI rule, $|Z| \leq 0.2 - 0.4$, have recently been found in p̄p annihilation at the Low Energy Antiproton Ring (LEAR) at CERN, as reviewed in Table 2.

The main purpose of this paper is to pursue the interpretation of these data in terms of the "shake-out" and "rearrangement" of an intrinsic s̄s component of the nucleon wave function as illustrated in Figs.1a,b, respectively. These mechanisms provide *a channel-dependent,*

non-universal modification of the naïve OZI prediction (1), and we propose tests of our interpretation. This should not be considered a violation of the OZI rule, because it does not involve disconnected quark diagrams, but rather connected diagrams involving higher Fock–space components in the nucleon wave function. Within this approach, we interpret the strong excess of ϕ production in S-wave p̄p annihilations in terms of the negative polarization of the nucleon's s̄s component indicated by EMC and subsequent results [34]. This interpretation could be tested by measurements of the $f_2'(1525)/f_2(1270)$ production ratio in P-wave annihilations, where there may be an enhancement over the naïve OZI expectations, and by experiments with polarized beams and polarized targets. We also mention a possible test of ϕ production within the intrinsic strangeness hypothesis in high-momentum transfer processes, via a difference in constituent counting rules from gluon-mediated production.

2 The "Shake–out" and "Rearrangement" of Intrinsic Strangeness in the Nucleon

We start with some general considerations on ϕ production via an intrinsic strangeness component of the nucleon. We adopt the following notation for the decomposition of the proton wave function:

$$|p>= x\sum_{X=0}^{\infty}|uudX> + z\sum_{X=0}^{\infty}|uud\bar{s}sX>, \tag{4}$$

where X stands for any number of gluons and light q̄q pairs, and the condition $|x|^2+|z|^2=1$ holds if we neglect the admixture of more than one $\bar{s}s$ pair. We consider two processes which are allowed by the OZI rule if such an intrinsic strangeness component is present, namely the "shake–out" illustrated in Fig.1a and the "rearrangement" illustrated in Fig.1b. A "shake–out" amplitude for $\bar{p}p$ annihilation into a state with either hidden strangeness such as the ϕ or open strangeness, is given generically by

$$M(\bar{p}p\to\bar{s}s+X)\simeq 2Re(xz^*)\ P(\bar{s}s), \tag{5}$$

where $P(\bar{s}s)$ is a projection factor which depends in particular on the final state considered: ϕ, $f_2'(1525)$, non–resonant $\bar{K}K$ pair, etc., though there may also be some dependence on the initial $\bar{p}p$ state considered. A "rearrangement" amplitude for producing a particular $\bar{s}s$ state is given generically by

$$M(\bar{p}p\to\bar{s}s+X)\simeq |z|^2\ T(\bar{s}s), \tag{6}$$

where the factor $T(\bar{s}s)$ will in general depend quite strongly on both the initial and final spin states, since the $\bar{s}$ and s come from different initial–state particles. For example, this mechanism may be expected to be unlikely to give a P–wave strangeonium state such as the $f_2'(1525)$ if the $\bar{p}p$ annihilation takes place from an S–wave state. The corresponding amplitudes for producing a light q̄q state with the same quantum numbers are not directly related to (5) and (6), but would be given generically by

$$M(\bar{p}p\to\bar{q}q+X)=|x|^2\ \left[P(\bar{q}q)\ or\ T(\bar{q}q)\right], \tag{7}$$

in analogous notation.

Defining Z as in equation (2), and assuming that the factors P, T are similar for light and strange quarks, we find

$$|Z| = 2\left|\frac{z}{x}\right| = 2\frac{|z|}{\sqrt{1-|z|^2}} \tag{8}$$

for the "shake–out" diagram and

$$|Z| = \frac{|z|^2}{|x|^2} = \frac{|z|^2}{1-|z|^2} \tag{9}$$

for the "rearrangement" one. In particular, the linear dependence (8) for shake-out processes allows $|Z|$ to be relatively large, even if $|z|^2$ is small. If we choose even one of the most striking values in Table 2, namely $|Z(\phi\pi/\omega\pi)| = 0.24 \pm 0.02$, we see from (8)-(9) that the $\bar{\mathrm{s}}\mathrm{s}$ admixture needed in the proton wave function is in the range

$$0.01 \leq |z|^2 \leq 0.19 \tag{10}$$

Such an admixture is not incompatible with data on open strangeness production in $\bar{\mathrm{p}}\mathrm{p}$ annihilation at rest, as we now discuss.

Our hypothesis that there are $\bar{\mathrm{s}}\mathrm{s}$ pairs "stored" in nucleons, that can be "shaken out" or "rearranged" in $\bar{\mathrm{p}}\mathrm{p}$ annihilation, can be confronted with the available data on strange particle production in annihilation at rest. Summing all measured channels containing kaons and correcting for unseen modes, the kaon yield is found to be [35]

$$Y_K = (4.74 \pm 0.22)\% \tag{11}$$

which is consistent with the independent determination of the yield of annihilations into pions alone [36]

$$Y_\pi = (95.4 \pm 1.8)\%. \tag{12}$$

Among the contributions to Y_K are the "shake-out" and "rearrangement" processes we discuss, and the creation of new $\bar{\mathrm{s}}\mathrm{s}$ pairs in the annihilation final state. Examples of the latter are provided by the kaonic decay modes of non-strange mesons such as the $f_2(1270)$, $a_2(1320)$ and $b_1(1235)$. Combining their production branching ratios with their probabilities for decay into final states containing $\bar{K}K$, one estimates a contribution to Y_K of $0.4-0.5\%$ of all annihilations. Most of the remainder of Y_K could be due to "shake-out" and "rearrangement" contributions of the order of 4 %, which is comparable with (10). Indeed, it follows from (5) that

$$Y_K = 4|x|^2|z|^2cos^2\varphi = 4(1-|z|^2)|z|^2cos^2\varphi, \tag{13}$$

where φ is the relative phase of the x and z (complex) coefficients. The value $Y_K \simeq 4\%$ therefore leads to the limit

$$|z|^2 \geq 0.01, \tag{14}$$

which is consistent with (10). The relative magnitude of the contribution from the creation of new $\bar{s}s$ pairs could in principle be probed by comparing Y_K (11) with the kaon yield in $\pi\pi$ scattering at the same centre-of-mass energy. The $\bar{K}K$ yield due to "shake-out" or "rearrangement" in $\bar{\mathrm{p}}\mathrm{p}$ annihilation could also have phase-space distribution different from

that of s̄s pair creation. The latter would tend to be central and with low relative momenta, whereas "shake-out" contributions could carry large momenta and emerge in the forward and backward directions from p̄p annihilation in flight. Indeed, the observed [37] backward peak in $\bar{p}p \rightarrow K^-K^+$ at $p = 0.5\ GeV/c$ was interpreted [1] as evidence for strange quarks in the proton. Recent experiments at LEAR and KEK confirm existence of the strong backward peak at p̄ momenta $p < 1\ GeV/c$ [38],[39].

Additional evidence for the intrinsic strangeness picture comes from the experimental data on double $\phi\phi$ production taken by the JETSET Collaboration at LEAR. Naïvely, one would expect [57] a cross section of the order of

$$\sigma(\bar{p}p \rightarrow \phi\phi) = tan^4\delta\ \sigma(\bar{p}p \rightarrow \omega\omega) \sim 10\ nb, \tag{15}$$

if both ϕ's were produced by independent OZI–violating couplings. The cross section measured [40] at 16 different antiproton momentum settings spanning the region between 1 and 2 GeV/c is however about 1500 nb, i.e. it exceeds the naïve OZI rule estimate given above by at least two orders of magnitude. The intrinsic strangeness model easily accommodates this experimental observation, which could be due to either "shake–out" or "rearrangement", with an amplitude $\sim |z|^2$. The limit (14) would imply then

$$\sigma(\bar{p}p \rightarrow \phi\phi) = \frac{|z|^4}{|x|^4}\ \sigma(\bar{p}p \rightarrow \omega\omega) \geq 250\ nb. \tag{16}$$

The experimental value of the cross section corresponds to $|z|^2 \simeq 0.025$. The connected diagrams involving intrinsic strange quarks will likely mask any possible glueball resonance contributions which are expected to be dominant among the disconnected diagrams. No such resonances are observed at present [40].

3 Data on ϕ Production in $\bar{p}p$ Annihilation at Rest

After this preparatory discussion of the intrinsic s̄s component of the nucleon and the "shake-out" and "rearrangement" processes, we now discuss specific features of ϕ production in p̄p annihilation at rest. The fact that the ratio of ϕ and ω yields in various individual channels exceeds the prediction of the naïve OZI rule has been known for some time. In particular, the bubble chamber data of [26]-[29] on $\bar{p}n$ annihilation could be combined to estimate $R_{\pi^-} = B.R.(\phi\pi^-)/B.R.(\omega\pi^-) = (83 \pm 25) \cdot 10^{-3}$. However, the statistics was limited to 54 events in the $\phi\pi^-$ channel [26]. We also mention the value of

$$R = \frac{g^2_{p\bar{p}\phi}}{g^2_{p\bar{p}\omega}} = 0.211 \div 0.276. \tag{17}$$

inferred from analyses of the proton vector isoscalar form factor [41], [42] in which the $\bar{N}N\phi$ and $\bar{N}N\omega$ coupling constants were treated as free parameters (see also [43]). This value is compared with measurements of ϕ/ω production ratios in Fig.2 [2].

[2] We note here in passing that a triply-strange baryon resonance has been seen [44] in the channel $\Omega^* \rightarrow \Omega\pi\pi$, which is naïvely OZI-disallowed, but would be allowed if there is a higher $|sss\bar{q}q>$ Fock-state component in the Ω wave function.

As we now review, the advent of high-statistics experiments at LEAR has brought a new era in p̄p annihilation studies, with larger excesses in ϕ production above the naïve OZI prediction established by the ASTERIX [22], Crystal Barrel [23] and OBELIX [24] collaborations, as shown in Fig.2 and Table 2.

The ASTERIX collaboration [22] has measured the ratios of ϕX and ωX final states with $X = \pi, \eta, \omega, \rho, \pi\pi$ in S- and P-wave p̄p annihilation. As seen in Table 2, the experimental values of R in different S-wave annihilation channels are mostly higher than the OZI prediction by a factor of 2 to 8. The most striking variation in this trend is the very large enhancement in the case $X = \pi$ in S-wave annihilations, by a factor 20 or so. However, in P-wave annihilations there is no corresponding enhancement in the cases $X = \pi$ and $X = \eta$, and only modest (if any) enhancement in the $X = \rho, \pi\pi$ channels, as can be seen by comparing the yields from the different types of target.

The Crystal Barrel collaboration [23] has measured the ratios of ϕX and ωX for $X = \pi^0, \eta$, $\pi^0\pi^0$ and γ final states in p̄p annihilation in liquid hydrogen. They confirmed the ASTERIX observation of a large deviation from the naïve OZI rule (1) in the case $X = \pi^0$, whilst the $X = \eta, \pi^0\pi^0$ cases deviate only slightly (if at all) from (1). However, their most striking result was an extremely large ratio in the case $X = \gamma$, which they found to be about 100 times higher than the naïve OZI prediction.

The OBELIX collaboration has complemented these results by measuring the $\phi X/\omega X$ ratios in n̄ annihilations in liquid hydrogen [25], and in p̄ annihilation on gaseous deuterium at different momenta of the spectator protons [24]. Large enhancements over the naïve OZI prediction (1) were found in both the cases $X = \pi^\pm$.

We draw the reader's attention to the following salient features of ϕ production in nucleon annihilation at rest.

1. The channels $\phi\pi$, $\phi\gamma$ exhibit strong enhancement over the naïve OZI prediction (1), whereas there are only smaller enhancements in the channels $\phi\rho$, $\phi\omega$, $\phi\pi\pi$ and no evidence of any enhancement in $\phi\eta$.

2. The amount of apparent OZI violation in annihilations at rest is much higher than what is seen in πp or pp scattering and higher-energy p̄p annihilation, as shown in Table 1 and Fig.2.

3. In cases where the initial p̄p state is known, the large enhancement of $\phi\pi$ appears to be restricted to the S-wave, with no large deviation from the naïve prediction (1) in any P-wave annihilation channel.

Any model of the large rate of ϕ production in p̄p annihilation at rest should be able to predict or accommodate these three channel-dependent features.

4 Alternative Models of ϕ Production

It has been suggested [45] that the enhancement of ϕ meson production in certain $\bar{N}N$ annihilation channels might be due to resonances. Specifically, if there existed a vector ($J^{PC} = 1^{--}$) $\phi\pi$ resonance close to the $\bar{N}N$ threshold, it might be possible to explain the selective enhancement of the $\phi\pi$ yield in S-wave annihilation, and the relative lack of ϕ's in

P-wave annihilation. The best candidate for such a state is one with mass $M = 1480 \pm 40$ MeV, width $\Gamma = 130 \pm 60$ MeV and quantum numbers $I = 1,\ J^{PC} = 1^{--}$, which was observed [46] in the $\phi\pi^0$ mass spectrum in the reaction $\pi^- p \to K^+ K^- \pi^0 n$ at 32.5 GeV/c, and dubbed the C-meson.

However, this resonance cannot explain the even larger enhancement recently observed in the $\phi\gamma$ channel, which is a final state with different quantum numbers. Moreover, the experimental status of the C-meson is unconfirmed. Although some experiments have found indications for its existence (for a review, see [47]), others have not. In particular, the ASTERIX collaboration [22] has established an upper limit of $3 \cdot 10^{-5}$ on the production of any $\phi\pi$ resonance in p̄ annihilation in a hydrogen gas target, and the Crystal Barrel collaboration has not seen the C-meson among $(\phi\pi^0)\pi^0$ final states in p̄ annihilation in a liquid hydrogen target [48]. The predicted [45] isoscalar partner of the C-meson which should couple to the $\phi\eta$ channel also was not observed, and no deviation from the naïve OZI rule has been detected in this mode (see Table 2). Therefore we discard the resonance interpretation of the apparent violation of the OZI rule.

Alternatively, it has been suggested [49],[50] that the ϕ mesons in the $\phi\pi$ final state might be due to final-state interactions of the K and K̄ in the $K^*\bar{K} + \bar{K}^*K$ channel that dominates the $KK\pi$ final state:

$$\bar{p}p \to K^*\bar{K} + \bar{K}^*K \to \phi\pi$$

One interesting test of this mechanism would be to see whether isospin I=1 amplitude of $\bar{p}p \to K^*\bar{K} + \bar{K}^*K$ is larger in S-wave annihilation than in P-wave annihilations. If not, the large ϕ excess in S-wave annihilations could not be explained. However, the concrete calculations of ϕ production [49], [50] made in different channels fall below the experimental data by factors of 2 to 6 or more. Moreover, strong cancellations are expected between different hadronic loop amplitudes [51], [52], so these calculations can only be considered as upper limits at best. Furthermore, as was pointed out in [53], the rescattering model cannot explain why the ratio $\phi\pi\pi/\omega\pi\pi$ is smaller than $\phi\pi/\omega\pi$, despite the fact that the $K^*\bar{K}^*$ final state is as copious as $K^*\bar{K} + K\bar{K}^*$ in $p\bar{p}$ annihilation. Therefore the rescattering interpretation of the apparent violations of the OZI rule meets serious difficulties.

5 Polarization of the Intrinsic Strangeness

As already mentioned above, we seek to explain ϕ enhancement in terms of the intrinsic strangeness component in the long–wavelength nucleon wave function. The key question to be addressed by this explanation is the channel dependence of the ϕ enhancement. As has been pointed out elsewhere [1],[54],[55], the $\bar{s}s$ component of the nucleon is expected to exhibit momentum and spin correlations that cause couplings to $\bar{s}s$ meson final states to be channel–dependent in general. We now construct a model for one aspect of this channel dependence suggested by experimental results on the polarization of strange quarks and antiquarks in the proton. Results from the EMC, SMC, E142 and E143 collaborations [34] indicate that

they have a net polarization opposite to the proton spin [56]:

$$\Delta s \equiv \int_0^1 dx[q_\uparrow(x) - q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)] = -0.08 \pm 0.03. \quad (18)$$

For the sake of simplicity, let us consider the possibility that all the s and $\bar{s}$ in the proton are polarized negatively, and none positively. The simplest wave function of this higher Fock-state component, consistent with the parity and spin constraints, corresponds to a spin-triplet S-wave $|\bar{s}s>$ state which is in a P wave relative to the "normal" $S = 1/2$ light $|uud>$ component. The projection of the relative orbital momentum on the spin axis in this model is $L_z = +1$, so that the total angular momentum of the nucleon remains 1/2 [3]. In this case, "shake–out" into the $^3S_1$ strangeonium state, namely the ϕ, is likely to dominate over other hidden strangeness states such as the P–wave $f_2'(1525)$. Now let us consider $\bar{p}p$ annihilation from a spin–triplet initial state, in which the $\bar{p}$ and p spins are parallel. In this case, $\bar{s}$ and s quarks in both nucleons "rearranged" during the annihilation will also have parallel spins, as in the naïve quark model wave function of the ϕ meson. Further, if the $p\bar{p}$ initial state is S–wave, the $\bar{s}s$ pair will probably also be in an S–wave also as in the ϕ meson. Therefore, we expect maximum enhancement of ϕ production in the $^3S_1$ channel, as observed in the $\phi\pi$ final state. This model predicts weaker enhancements in the $^1S_0$ channel, as observed.

This model also suggests qualitatively why ϕ production may be enhanced more in $\bar{p}p$ annihilation at rest than in the other $\bar{p}p$, pp, and πp interactions. The reason is that higher–energy collisions involve an increasing mixture of partial waves, implying that the S–wave state "rearrangement" that favours ϕ production becomes progressively more diluted. A corollary of this observation is that we would expect the large enhancement of $\bar{N}N \to \phi\pi$ to diminish as the centre–of–mass energy is increased.

Thus our heuristic polarization model predicts or accommodates the three salient features of the data noted earlier. However, it should be emphasized that our model is idealized. The approximation that all the $\bar{s}$ and s inside a proton are polarized antiparallel to its spin is very crude, the polarizations could be altered during the "shake–out" or "rearrangement" processes, and diagrams like those in Fig.1b could make contributions to the production of ϕ 's and other $\bar{s}s$ mesons that are independent of the initial spin state.

The reader might expect that the $\phi\eta/\omega\eta$ ratio would be enhanced at least as strongly as the $\phi\pi/\omega\pi$ ratio, since the favoured $^3S_1$ initial $\bar{p}p$ state also contributes. However, in this channel there are additional connected quark diagrams, (shown in Fig.3) because the η has a substantial ($\approx 50\%$) $\bar{s}s$ -component. Fig.3a features the rearrangement of two $\bar{s}s$ pairs from the initial nucleon wave functions, and would require a spin-flip of at least one of the s̄ or s to produce the $\phi\eta$ final state from the $^3S_1$ initial state, according to our idealized model. Fig.3b involves the annihilation of one $\bar{s}s$ pair and the subsequent creation of a new $\bar{s}s$ pair, and may be at least as important as Fig.3a.

The diagrams in Fig.3 will interfere with the diagrams of Fig.1 that contribute to $\phi\pi$

[3] We do not discuss here dynamical effects which can be responsible for such a wave function.

production in our model. We do not know a priori whether this interference is constructive or destructive, enhancing or suppressing the yield of $\phi\eta$ relative to $\omega\eta$. However, the fact the $\bar{s}s$ components of the η and η' wave functions have opposite signs means that the interferences in the $\phi\eta$ and $\phi\eta'$ production amplitudes must have opposite signs, enhancing one while suppressing the other. The data in Table 2 tell us that the $\phi\eta$ channel is suppressed, enabling us to predict that the $\phi\eta'$ channel should be enhanced. Since both ϕ and η' are heavier than the proton, this prediction can only be checked in $\bar{p}p$ annihilation in flight. However, it should be noted that the favoured S-wave channel will be diluted for in-flight annihilation.

It would be interesting to explore the dependence of the amount of the apparent OZI violation not only on the spin of the initial state but, for instance, on the momentum transfer. In an early experiment on ϕ production in $\pi^{\pm}N \to \phi N$ interaction [13] it was found that the $d\sigma/dt$ distribution of ϕ production at large t differs significantly from the one for ω-meson, leading to the increase of ϕ/ω ratio at large t. This effect was especially marked for unnatural-parity exchange.[4] The production of the ϕ in antiproton annihilation at rest also seems to exhibit a dependence of the apparent OZI rule violation on the momentum transfer. In Fig.4 the dependence of the ratios $R = \phi X/\omega X$ in different reactions is shown as a function of momentum transfer in $\bar{p}p \to \phi X$ (see also Fig.5). The deviation from the naïve OZI rule prediction increases with momentum transfer.

However one should be cautious in interpreting the dependence in Fig.4 as a rigorous proof that the apparent OZI rule violation increases with momentum transfer. In the two-body antiproton annihilations at rest: $\bar{p}p \to \phi(\omega) + X$, the momentum transfer to the ω is always higher than the momentum transfer to the ϕ. It is possible to compare ϕ and ω production at the same momentum transfer in annihilation in flight or in the $\phi(\omega)\pi\pi$ channel for annihilation at rest.

The intrinsic strangeness model can also explain rather naturally a number of experimental facts on strange baryon production. For instance, it is well known [59] that in the reaction

$$\bar{p} + p \to \Lambda + \bar{\Lambda} \tag{19}$$

the spins of the Λ's exhibit strong correlations. Although both spin singlet and triplet final states are possible, the spin singlet fraction is zero within statistical errors. The spin of the Λ is largely carried by the spin of the strange quark, so the $\bar{s}s$ pair in the final state of (19) must mostly have parallel spins. This could naturally be expected in the intrinsic strangeness model: a spin-triplet $\bar{s}s$ pair in the proton or antiproton may simply dissociate into a $\Lambda\bar{\Lambda}$ pair, conserving their spin correlation, which leads to a spin-triplet final state for the two hyperons.

6 Possible Tests of the Model

Possible tests of our model include checks on the spin-dependences of amplitudes that violate the naïve OZI rule, and on their momentum transfer dependences.

[4] We thank E.Klempt and C.Strassburger who brought our attention to these results.

1. The arguments for $\phi\pi$ enhancement in production from the ${}^3S_1$ initial state can be extended to other $\bar{s}s$ resonances, in particular to production of the $f_2'(1525)$ compared to the $f_2(1270)$. Using the quadratic mass formula, as used to obtain the naïve OZI estimate (1), we obtain

$$R' = f_2'(1525)/f_2(1270) = 16 \cdot 10^{-3} \tag{20}$$

before applying phase space corrections. This may actually be an overestimate: the OZI–forbidden decay $f_2' \to \pi\pi$ has been seen at a low rate relative to the OZI–allowed $\bar{K}K$ decay mode, corresponding to

$$R' = f_2'(1525)/f_2(1270) = 3 \cdot 10^{-3}. \tag{21}$$

The $f_2'(1525)$ was not seen by bubble chamber experiments in annihilations at rest, which gave an upper limit on the yield for $\bar{p}p \to \pi^0 f_2'$ of $3.8 \cdot 10^{-3}$ [60]. Comparison with the yield of f_2 production [58] in the $\bar{p}p \to \pi^0 f_2$ channel of $(3.9 \pm 1.1) \cdot 10^{-3}$ shows that the present experimental information on the ratio f_2'/f_2 ratio is rather inconclusive.

Since the f_2' is a spin–triplet P–wave state in the naïve quark model, the type of argument we used to motivate enhancement of ϕ production in ${}^3S_1$ $\bar{p}p$ annihilations would favour a large f_2'/f_2 ratio in ${}^3P_1$ $\bar{p}p$ annihilations. It is interesting to note that the f_2 yield in P–wave $\bar{p}p$ annihilation is known to be five times greater than in the S-wave: $Y^P_{f_2} = 1.85 \pm 0.24\%$ [58]. If the above prediction of enhanced f_2' production is correct, and the effect is as large as in the ${}^3S_1$ ϕ production case, the signal for f_2' production in P–wave $\bar{p}p$ annihilation should be clearly visible, with the branching ratio of $\bar{p}p \to \pi^0 f_2'$ possibly as large as 0.1-0.2 %. This suggestion could be tested in data recently taken by the OBELIX collaboration on $\bar{p}p$ annihilation in gaseous hydrogen at small pressure. There are already some data on f_2' production in $\bar{p}p$ annihilation in flight [21],[61] indicating substantial apparent violation of the naïve OZI prediction (20)-(21), but the statistics in these experiments was scarce, and new high–statistics data are needed.

Ref. [62] considered production of f_2' in the $\bar{p}p \to f_2'\pi^0$ reaction via final-state K^*K and $\rho\pi$ interactions. The calculated production rates of f_2' from the S or P states were rather small, of the order 10^{-6}. This means that, if any deviation from the naïve OZI rule is established for f_2', it could not be explained by rescattering.

2. Since annihilation at higher energies involves an increasing mixture of partial waves, the S-wave state “rearrangement” that favours, for example, $\phi\pi$ state production from the ${}^3S_1$ initial state, becomes more diluted (see the discussion in Sect.5). We expect therefore that the $\phi\pi/\omega\pi$ ratio measured in annihilation in flight will decline, following the decreasing admixture of the ${}^3S_1$ state. Recent preliminary results from the Crystal Barrel experiment [63] indicate that the branching ratio of the $\phi\pi^0$ channel decreases approximately 5 times when the momentum of the antiproton is increased to 600 MeV/c whereas the branching ratio of the K^*K stays constant. This is consistent with the fact that at 600 MeV/c the percentage of S-wave in $p\bar{p}$ annihilation is about $14 - 20\%$ [64].

3. It is important to check the spin dependence of the OZI-violating $\bar{p}p \to \phi\phi$ amplitude. Our model predicts that an even larger deviation from the naïve OZI rule should be seen in an experiment with polarized beam and target when an initial spin-triplet state is prepared.

In a spin-singlet state the apparent OZI violation should, according to our model, be less pronounced.

4. An interesting possibility for testing the model is provided by the $\phi\pi\pi$ final state where, contrary to two-particle channels for ϕ production, annihilation in the same partial wave is possible from both the spin-triplet and spin-singlet states. A spin-parity analysis of the Dalitz plot for $\bar{p}p \to \phi\pi\pi$ annihilation should demonstrate dominance of the ${}^3S_1$ initial state, if our hypothesis is correct.

5. It is interesting to study the spin structure of the OZI-allowed process

$$\bar{p} + p \to K^* + \bar{K}^* \tag{22}$$

If intrinsic strangeness manifests itself also in OZI-allowed processes, spin correlations should appear in the final state. For example, when the initial $\bar{p}p$ pair is in the spin-triplet state, the final $K^*\bar{K}^*$ channel should be dominated by the $S = 2$ state.

6. The largest violation of the naïve OZI rule occurs in the $\phi\gamma$ channel (see Table 2). This channel was measured for antiproton annihilation in liquid, where S-wave annihilation is dominant. The $\phi\gamma$ final state is possible either from spin-singlet ${}^1S_0$ or from spin-triplet ${}^3P_{0,1,2}$ states. If the ϕ production is really enhanced for spin-triplet states, then one would expect that the ratio $\phi\gamma/\omega\gamma$ will increase for annihilation in hydrogen gas at normal temperature and pressure or at low pressure, where the P-wave annihilation is dominant.

7. Another possible test of the ϕ production mechanism is provided by its final–state decay angular distribution, as measured in the reaction

$$p + p \quad \longrightarrow \quad \phi + X, \tag{23}$$

$$\hookrightarrow e^+e^- \tag{24}$$

for example. Since our production mechanism proceeds via a vertex $(\bar{s}\gamma_\mu s)\phi_\mu$, where the s and $\bar{s}$ come from the initial–state proton wavefunctions, we expect an angular distribution

$$W(\theta) = 1 + cos^2\theta \tag{25}$$

for the e^+e^- pair, where θ is the angle of the e^- (e^+) relative to the incident proton beam direction measured in the rest frame of the ϕ.

8. An interesting test of the ϕ production mechanism involves an application of the constituent counting rules for high momentum–transfer collisions [66],[67]:

$$\frac{d\sigma}{dt}^{(A+B\to C+D)}_{\theta_{cm}\ fixed} = \frac{1}{s^{n_A+n_B+n_C+n_D-2}}\ f(s/t), \tag{26}$$

where $n_{A,B,C,D}$ are the numbers of constituents participating in the hard collision. Consider for definiteness the processes $\pi p \to \phi n$ and $\bar{p}p \to \phi\pi$, compared with $\pi p \to \omega n$ and $\bar{p}p \to \omega\pi$. The latter reactions can proceed via valence quarks in the participating hadrons, in particular, via the $\bar{q}q$ component of the ω, and the differential cross–sections should therefore fall off as

s^{-8}. On the other hand, if ϕ mesons are produced entirely via the $|uuds\bar{s}>$ components of the nucleon wave functions, the ϕ differential cross–sections should fall off as s^{-12}, resulting in a disappearance of the apparent OZI violation at high energies. On the other hand, if ϕ production proceeds via a three-gluon intermediate state, this can result in an s^{-9} behaviour of the differential cross–section. To be conclusive, such a quark counting rule analysis should only be made at energies where the validity of (26) is established, e.g. above 10 GeV. However, qualitative features of this type may also appear at low energies. The trend for the naïve OZI rule (1) to become more accurate at high energies (see Fig.2) and the different $t-$dependences in $\pi p \rightarrow \phi n$ and $\pi p \rightarrow \omega n$ shown in Fig.5 are clearly consistent with the expectations of the quark counting rules, even though the latter are not strictly applicable.

9. The studies of angular distributions of ϕ and ω production for annihilation in flight $\bar{p}p \rightarrow \phi(\omega)\pi$ are interesting since these distributions should be different if ϕ and ω production mechanisms are not the same. Such a feature was already noted [19] in a bubble chamber experiment on $\bar{p}p \rightarrow \phi\pi\pi$ and $\omega\pi\pi$, albeit with low statistics.

10. The largest momentum transfer in ϕ production by stopped antiproton annihilation is available in the so-called Pontecorvo reaction

$$\bar{p} + d \rightarrow \phi + n \tag{27}$$

We may therefore expect very high ϕ/ω ratios in reactions of this type.

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Table 1. The ratios $R = \phi X/\omega X$ for production of the ϕ and ω - mesons in pp, $\bar{p}p$ and πp interactions at P_L different from zero. The parameter Z of the OZI-rule violation is calculated for $\delta = \Theta - \Theta_i = 3.7^0$, assuming identical phases of the ϕ and ω production amplitudes.

Initial state	P_L (GeV/c)	Final state X	$R = \phi X/\omega X \cdot 10^3$	$\|Z\|$ (%)	Refs.
$\pi^+ n$	1.54-2.6	p	21.0 ± 11.0	8 ± 4	[9],[10]
$\pi^+ p$	3.54	$\pi^+ p$	19.0 ± 11.0	7 ± 4	[11]
$\pi^- p$	5-6	n	3.5 ± 1.0	0.5 ± 0.8	[12]
$\pi^- p$	6	n	3.2 ± 0.4	0.8 ± 0.4	[13]
$\pi^- p$	10	$\pi^- p$	6.0 ± 3.0	1.3 ± 2.0	[14]
$\pi^- p$	19	$2\pi^-\pi^+ p$	5.0^{+5}_{-2}	0.6 ± 2.5	[15]
$\pi^- p$	360	X	14.0 ± 6.0	5 ± 3	[16]
pp	10	pp	20.0 ± 5.0	8 ± 2	[14]
pp	24	pp	26.5 ± 18.8	10 ± 6	[17]
pp	24	$\pi^+\pi^- pp$	1.2 ± 0.8	3 ± 1	[17]
pp	24	pp m$\pi^+\pi^-$, m=0,1,2	19.0 ± 7.0	7 ± 3	[17]
pp	360	X	4.0 ± 5.0	0.1 ± 4	[18]
$\bar{p}p$	0.7	$\pi^+\pi^-$	$19.0 \pm 5^{*)}$	7 ± 2	[19]
$\bar{p}p$	0.7	ρ^0	$13.0 \pm 4^{*)}$	5 ± 2	[19]
$\bar{p}p$	1.2	$\pi^+\pi^-$	$11.0 \pm^{+3}_{-4}$	4 ± 1	[20]
$\bar{p}p$	2.3	$\pi^+\pi^-$	17.5 ± 3.4	7 ± 1	[21]
$\bar{p}p$	3.6	$\pi^+\pi^-$	9.0^{+4}_{-7}	3 ± 3	[20]

$^{*)}$ corrected for phase space.

TABLE 2. The ratios $R = \phi X/\omega X$ for production of the ϕ and ω - mesons in antinucleon annihilation at rest. The parameter Z of the OZI-rule violation is calculated as in Table 1. The data are given for annihilation in liquid hydrogen target (percentage of annihilation from P-wave is $\sim 10-20\%$), gas target (∼61% P-wave) and LX-trigger [22] (∼86-91% P-wave).

Final state	Initial states	B.R.$\cdot 10^4$	$R \cdot 10^3$	$\lvert Z \rvert$ (%)	Comments
$\phi\gamma$	$^1S_0, ^3P_J$	0.17 ± 0.04	250 ± 89	42 ± 8	liquid,[23]
$\phi\pi^0$	$^3S_1, ^1P_1$	5.5 ± 0.7	96 ± 15	24 ± 2	liquid,[23]
$\phi\pi^0$		1.9 ± 0.5			gas, [22]
$\phi\pi^0$		0.3 ± 0.3			LX-trigger, [22]
$\phi\pi^-$	$^3S_1, ^1P_1$	9.0 ± 1.1	83 ± 25	22 ± 4	liquid,[26]-[29]
$\phi\pi^-$		14.8 ± 1.1	133 ± 26	29 ± 3	$\bar{p}d, p < 200\ MeV/c$, [24]
$\phi\pi^-$			113 ± 30	27 ± 4	$\bar{p}d, p > 400\ MeV/c$, [24]
$\phi\pi^+$			110 ± 15	26 ± 2	$\bar{n}p$, [24]
$\phi\eta$	$^3S_1, ^1P_1$	0.9 ± 0.3	6.0 ± 2.0	1.3 ± 1.2	liquid,[23]
$\phi\eta$		0.37 ± 0.09			gas, [22]
$\phi\eta$		0.41 ± 0.16			LX-trigger, [22]
$\phi\rho$	$^1S_0, ^3P_J$	3.4 ± 0.8	6.3 ± 1.6	1.4 ± 1.0	gas, [22],[32]
$\phi\rho$		4.4 ± 1.2	7.5 ± 2.4	2.1 ± 1.2	LX-trigger, [22],[32]
$\phi\omega$	$^1S_0, ^3P_{0,2}$	6.3 ± 2.3	19 ± 7	7 ± 4	liquid, [31],[33]
$\phi\omega$		3.0 ± 1.1			gas, [22]
$\phi\omega$		4.2 ± 1.4			LX-trigger, [22]
$\phi\pi^0\pi^0$	$^{1,3}S_{0,1}, ^{1,3}P_J$	1.2 ± 0.6	6.0 ± 3.0	1.3 ± 2.0	liquid,[23]
$\phi\pi^-\pi^+$		4.6 ± 0.9	7.0 ± 1.4	1.9 ± 0.8	liquid,[30]
$\phi X, X = \pi^+\pi^-, \rho$		5.4 ± 1.0	7.9 ± 1.7	2.4 ± 1.0	gas, [22],[32]
$\phi X, X = \pi^+\pi^-, \rho$		7.7 ± 1.7	11.0 ± 3.0	4.0 ± 1.4	LX-trigger, [22],[32]

FIGURE CAPTIONS

Figure 1. a) Production of a ϕ meson in $\bar{p}p$ annihilation by the OZI-allowed process of $\bar{s}s$ rearrangement from $|uud\bar{s}s>$ components of the proton wave function.

b) Shake-out of a ϕ meson from a $|uud\bar{s}s>$ component of the proton wave function.

Figure 2. Ratios $R = \phi X/\omega X$ in different reactions at increasing momenta p.

Figure 3. Diagrams contributing to the double production of $\bar{s}s$ mesons via a) double annihilation, b) via creation of an additional $\bar{s}s$ pair, and c) via double shake-out of $\bar{s}s$ pairs in $|uud\bar{s}s>$ components.

Figure 4. Dependence of the ratios $R = \phi X/\omega X$ in different reactions of stopped antiproton annihilation in hydrogen on momentum transfer in $\bar{p}p \to \phi X$. Experimental data are from Table 2.

Figure 5. Dependences of the branching ratios of ϕX and ωX in different channels of stopped antiproton annihilation in hydrogen on momentum transfer. Experimental data are from Table 2. The solid (lowest) and dash-dotted (highest) lines are the $t-$dependences measured in $\pi p \to \phi n$ and $\pi p \to \omega n$ reactions, respectively, with relative normalization fixed to be the same as for the experimental cross sections [13]. The dotted line has the same functional dependence as the solid line, but is normalized to fit the $\bar{p}p \to \phi\omega, \phi\pi$ data.

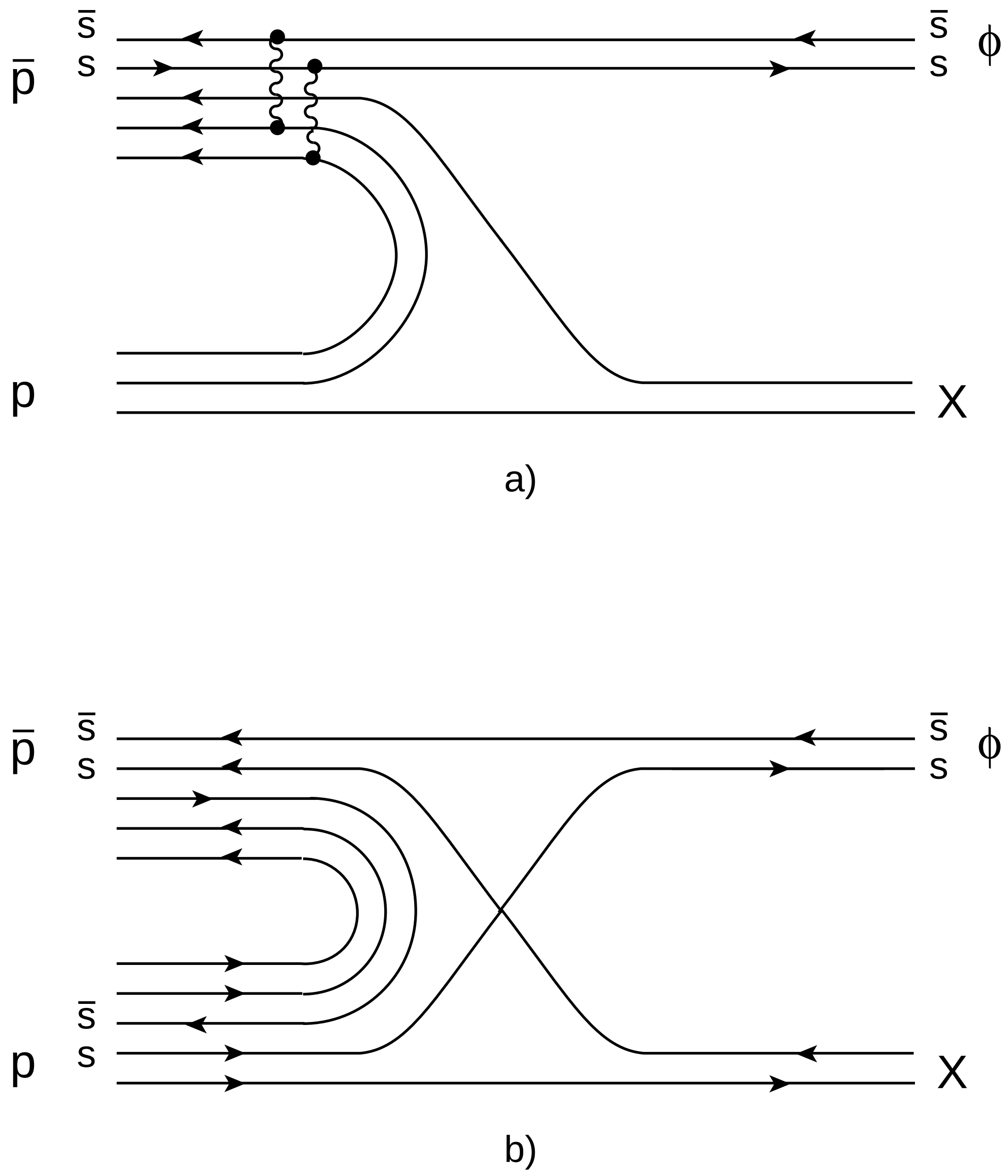
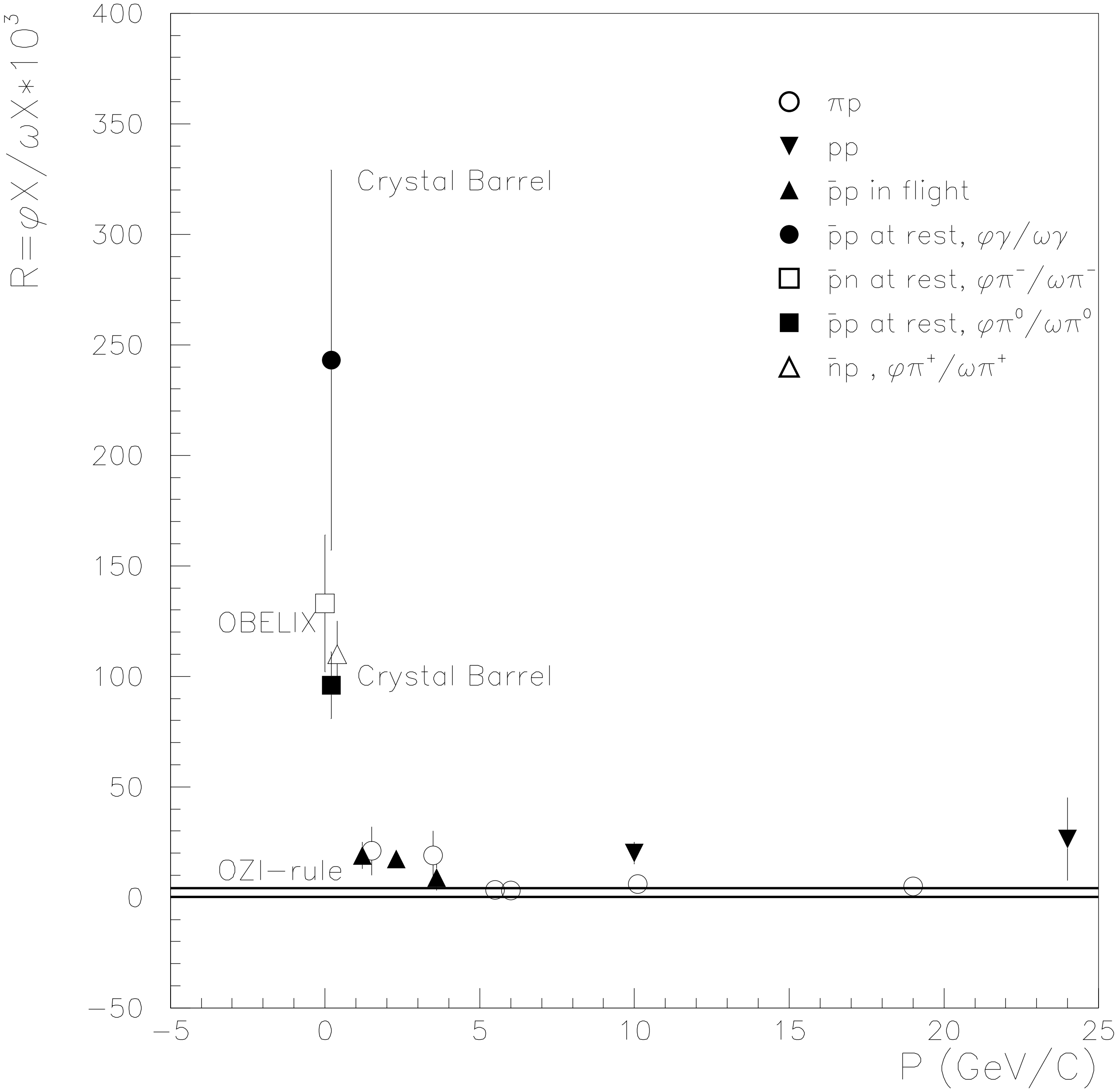
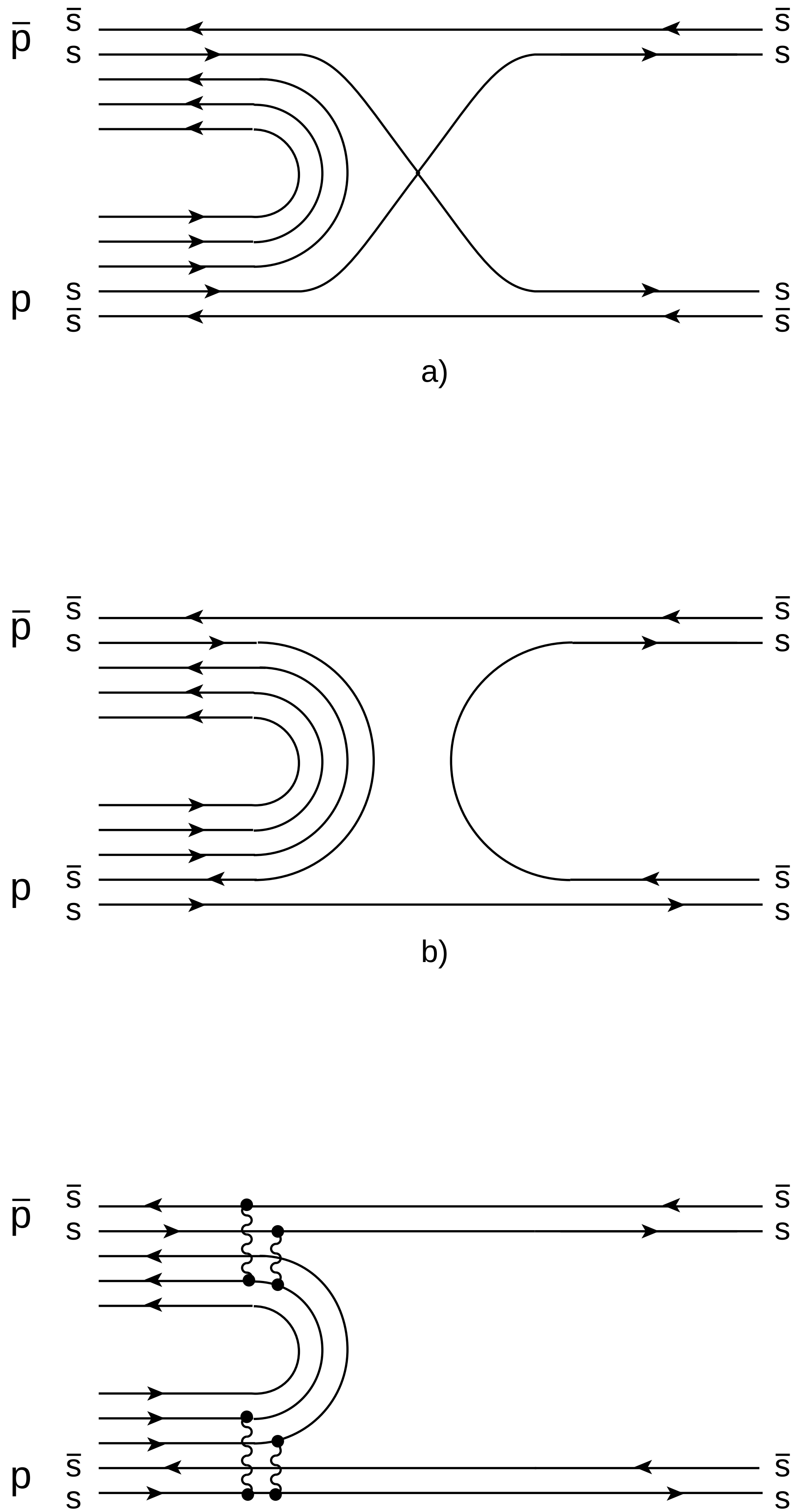


Fig. 1



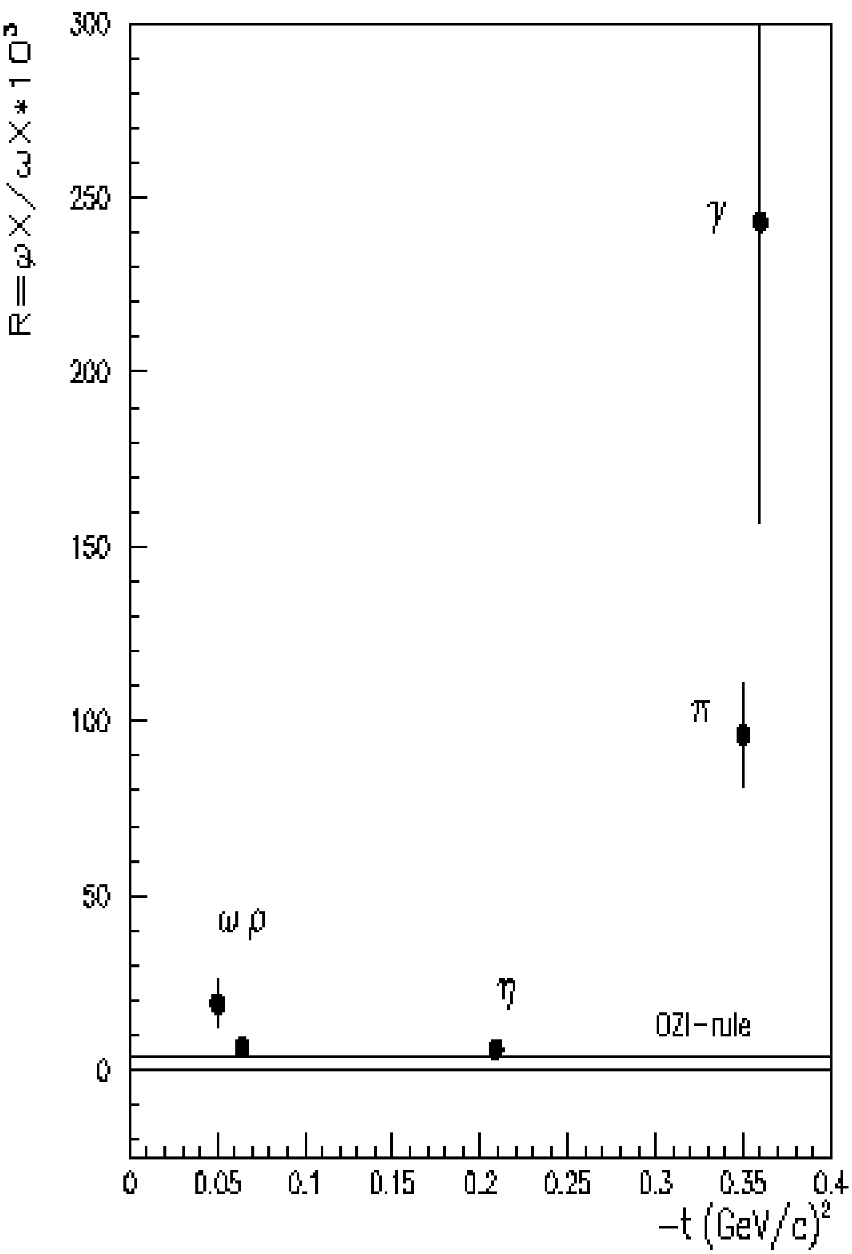
$R=\varphi X/\omega X*10^3$
400
350
300
250
200
150
100
50
0
−50
−5
0
5
10
15
20
25
P (GeV/C)
πp
pp
$\bar{p}p$ in flight
$\bar{p}p$ at rest, $\varphi\gamma/\omega\gamma$
$\bar{p}n$ at rest, $\varphi\pi^-/\omega\pi^-$
$\bar{p}p$ at rest, $\varphi\pi^0/\omega\pi^0$
$\bar{n}p$, $\varphi\pi^+/\omega\pi^+$
Crystal Barrel
OBELIX
Crystal Barrel
OZI−rule

Fig. 2



$\bar{p}$
$\bar{s}$
s
p
s
$\bar{s}$
$\bar{s}$
s
s
$\bar{s}$
a)
$\bar{p}$
$\bar{s}$
s
p
$\bar{s}$
s
$\bar{s}$
s
$\bar{s}$
s
b)
$\bar{p}$
$\bar{s}$
s
p
$\bar{s}$
s
$\bar{s}$
s
$\bar{s}$
s
c)

Fig. 3



$R=\varphi X/\omega X*10^3$
300
250
200
150
100
50
0
γ
π
$\omega\,\rho$
η
OZI-rule
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
$-t\ (GeV/c)^2$

Fig. 4

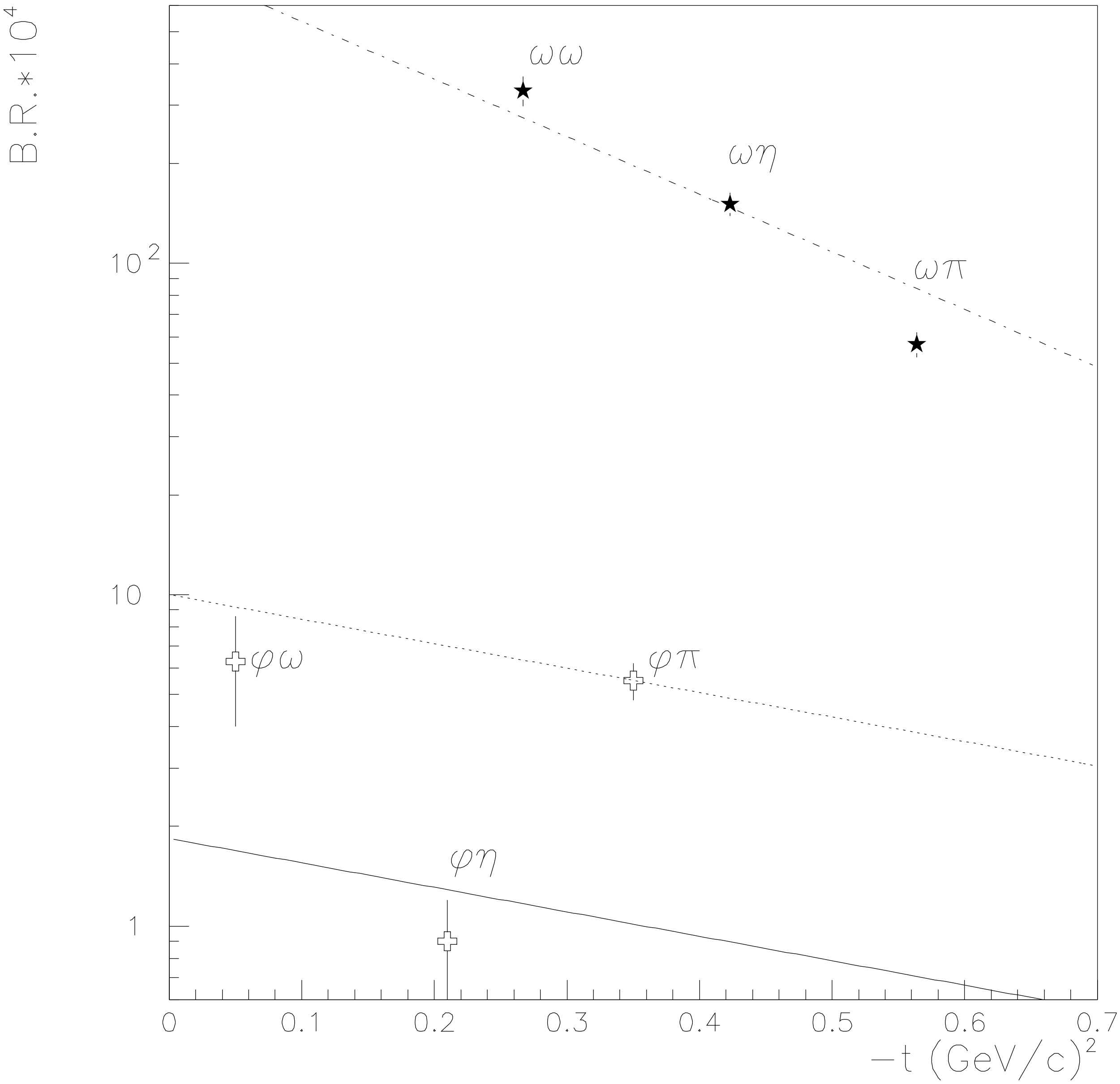


Fig. 5